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A COMPARISON OF THE DETECTION CAPABILITIES OF SINGLE FREQUENCY,--ETC(U)

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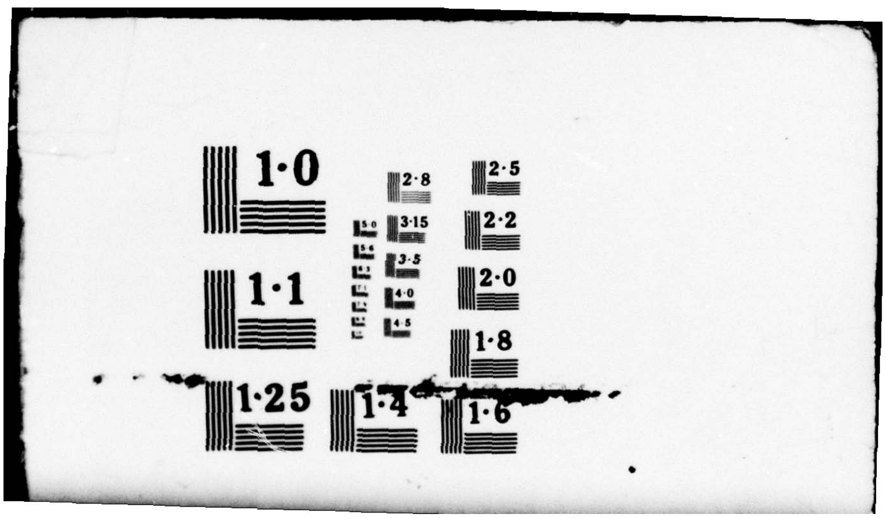
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NEL Technical Memo

A Comparison of the Detection Capabilities of Single Frequency, Frequency Modulated, and Noise Pulse Sonars for LORAD

J. L. Stewart, W. B. Allen, and R. M. Zarnowitz

This memorandum has been prepared for the information of others working in allied fields at NEL, and for limited distribution outside the Laboratory.

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1. General

a. Systems

It is the purpose of this memorandum to compare the detection capabilities of the sonar systems which employ "single frequency", frequency modulated and noise pulses with each processed in the manner typical of that technique. It is specifically not the intent of this memorandum to consider search rate, range and bearing localization and range rate determination. Nor is it the intent of the memorandum to propose an optimum processing for each of the different techniques but rather to choose a processing which will emphasize the similarities where they exist in order to bring out the significant differences. In order to facilitate the comparison, the output bandwidth of the processing system will be made equal to the reciprocal of the pulse duration. The reasons for this condition will be discussed in the report.

b. Reverberation

The reverberation level for the first surface convergence zone and sea state 2 which is given in section d below is that observed by NEL Code 2233 by omnidirectional pinging at 1 kc with one second pulses. It will be assumed that reverberation will decrease with pulse duration below one second and be independent of pulse durations longer than 5 seconds up to 30 seconds when neighboring bottom reverberation interferes.

c. Noise

It is assumed that the limiting noise is that due to the array platform and that this noise field is essentially

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omnidirectional with a continuous spectrum of level comparable with the ambient sea noise at about a sea state 4. This agrees with the observations on the submarine which will be the platform for the LORAD research array.

d. LORAD Parameters

These basic parameters are those observed by NEL Code 2233, for an operating frequency $f_o = 1$ kc.

Two way transmission loss,

first zone : $2\ H_I = +158$ db

second zone : $2\ H_{II} = +168$ db

third zone : $2\ H_{III} = +176$ db

Reverberation level $(RL)_o = -119$ db

(first zone, omnidirectional, one second pulse, sea state 2)

RL decreases with pulse duration T_p below 1 sec.

RL is constant for pulse durations T_p longer than 5 sec.

Bandwidth of reverberation for long single frequency pings is the order of 1 cps at 1 kc.

Target strength: $T = 20$ db

These equipment parameters are for the LORAD research system under construction at NEL.

Receiver beamwidth $\phi = 3^\circ$ (horizontal line array of 50 elements $n = 50$)

Projector front-to-back ratio > 10 db, which insonifies only one of the horizontal 3° sectors observed by the receiver.

Spectrum level of platform noise $N_1 = -33$ db/cps relative to 1 μbar.

e. Calculations

It is hoped that the calculations which follow are precise within a factor of 2 or 3 db. Calculations have been rounded off to this accuracy.

2. Single Frequency Pulse: Ping

a. System

The signal is an original single frequency which has been modulated with a rectangular pulse of duration Tp and passed through a filter of bandwidth $\Delta f = 1/T_p$. The processing system in the receiver consists simply of a bank of filters of the same bandwidth $\Delta f = 1/T_p$ separated Δf apart to detect doppler differences.

b. Reverberation

$$RL = (RL)_o + 10 \log (\phi /360) + 10 \log T_p$$

$$RL = -119 + 10 \log (3/360) + 10 \log T_p$$

$$= -119 - 21 + 10 \log T_p$$

$$= -140 + 10 \log T_p$$

If the echo level is E, then echo to absolute reverberation level R is given by

$$E - R = -2H + T - RL$$

$$E - R = -158 + 20 + 140 - 10 \log T_p$$

$$= 2 - 10 \log T_p$$

If now Δf is the signal bandwidth for a given pulse duration Tp, and Δr is the resolvable range increment or ping length for that pulse duration, then

when $E - R = 0$ db, $T_p \approx 1$ sec, $\Delta f = 1$ cps, $\Delta r = 1000$ yds

when $E - R = 10$ db, $T_p \approx 0.1$ sec, $\Delta f = 10$ cps, $\Delta r = 100$ yds

Because the RL of the first zone does not increase for pulses of 5 seconds or longer duration which is consistent with the 3 mile extent in range of the zone, and because of the finite 1 cps bandwidth of the reverberation for long pulses, there exist the possibility that 30 second single frequency pulse with 1/30 cps filter will show an echo 7 db above the reverberation. This value is peculiar to the first zone and to the receiver beamwidth chosen for this system and the corresponding value is insignificant for the second and third zones assuming 6 and 9 mile extents in range. If RL and -2H for the succeeding zones vary in the same manner with range, E - R will be independent of range.

c. Noise

$$N = N_1 + 10 \log (1/n) + 10 \log \Delta f$$

$$= -33 - 17 + 10 \log \Delta f = -50 + 10 \log \Delta f$$

The echo-to-noise level is then given by

$$E - N = S_o + T - 2H - N$$

where S_o is the axial source level in μby. Solving for S_o, we have

$$S_o = (E - N) + N - T + 2H$$

$$= (E - N) - 50 + 10 \log \Delta f - 20 + 2H$$

In (b) above a pulse length $T_p = 0.1$ secs gave an echo 10 db above reverberation. If we wish also to have an echo 10 db above noise for that system, we have

For $E - N = 10$ db, $\Delta f = 10$ cps ($E - R = 10$ db, $\Delta r = 100$ yds)

I Zone $S_o = 10 - 50 + 10 - 20 + 158 = \underline{108 \text{ μby}}$

II Zone $S_o = 10 - 50 + 10 - 20 + 168 = \underline{118 \text{ μby}}$

III Zone $S_o = 10 - 50 + 10 - 20 + 176 = \underline{126 \text{ μby}}$

d. Doppler Shift (Δf_d)

For 1 knot $\Delta f_d = \frac{2vf}{c} = 0.7$ cps

where v is the target velocity, c is the velocity of sound.

For 15 knots $\Delta f_d = 0.7 \times 15 = 10.5$ cps.

Because the bandwidth of reverberation for long single frequency pings is the order of 1 cps, pulses of 1 second duration or longer should then be able to detect 2 knot submarines at better E - R than for zero doppler but how much better depends upon the tail of the frequency distribution of reverberation which is unknown.

3. FM Pulse:

a. System

In this discussion the FM pulse sonar will transmit a short pulse during which the frequency is linearly swept through a bandwidth Δf_{FM} and the echo multiplied by an identical or similar pulse generated locally at the desired time. The product of the two signals is sent through a bank of bandpass filters to a display device to indicate range or doppler differences.

In an FM pulse sonar described above the output reverberation level is given by:

$$R = R_1 \Delta r_{FM} = R_1 \frac{\Delta F}{\Delta f_{FM}} T_{FM} \frac{c}{2} \qquad (1)$$

where F is the output filter bandwidth and T_{FM} is the FM pulse duration
where R_1 is the reverberation from a unit range interval, and Δr_{FM} is the range increment for the FM sonar.

The output noise level is:

$$N = N_1 \Delta F \qquad (2)$$

where R_1 and N_1 included the effect of the receiver directivity

Now it is required to reduce the output reverberation level to the absolute reverberation level, R, which is 10 db below the echo level, E, as discussed in the pulsed "single frequency" case. This obviously requires that the effective ping length, Δr_{FM}, of the FM sonar equal the ping length, Δr_r, of the "single frequency" sonar.

$$\frac{\Delta F}{\Delta f_{FM}} T_{FM} \frac{c}{2} = T_r \frac{c}{2} = \frac{c}{2\Delta f_r} \qquad (3)$$

There are three variables ΔF, Δf_{FM}, and T_{FM} to consider, only one of which, ΔF, uniquely determines the output noise level N.

Let us consider ΔF, first. There is a minimum value, ΔF_{min}, which is determined by the condition that the targets of interest stay within the range interval Δr_{FM} for a time equal to or longer than the response time $1/\Delta F$ of the output filter. Thus where v is the maximum range rate for the targets

$$\frac{1}{\Delta F} \leq \frac{\Delta r_{FM}}{v} \qquad (4)$$

$$\frac{1}{\Delta F} \leq \frac{1}{v} \frac{\Delta F}{\Delta f_{FM}} T_{FM} \frac{c}{2}$$

For the equality:

$$\Delta F_{MIN} = \left(\frac{2v}{c} \frac{\Delta f_{FM}}{T_{FM}} \right)^{1/2}$$

Under the condition $\Delta F \geq \Delta F_{min}$, one may chose essentially any $\Delta F < \Delta f_{FM}$. In selecting this output filter ΔF, the choice must be made between a narrow band filter and lower source level or a broad band filter and higher source level.

The value of ΔF selected above, and the value of R desired fixes the ratio $^{T_{FM}}/_{\Delta f_{FM}}$ which is the reciprocal of the frequency sweep rate $^{df}/_{dt}$. It is obvious that the pulse length T_{FM} cannot be smaller than the response time $^{1}/_{\Delta F}$ of the output filters without decreasing both the echo and the variable part of the reverberation relative to noise, and thus cannot improve detection. Subject to the condition $\Delta F \cdot T_{FM} \geq 1$, one can choose any T_{FM} and, from equation 1, obtain the corresponding input or signal bandwidth Δf_{FM} which yields the sweep rate $^{df}/_{dt}$ determined by the selection of ΔF and R above. The smallest pair of values are those for which $T_{FM} = {}^{1}/\Delta F$, and $\Delta f_{FM} = \Delta f_{p}$ from the condition $\Delta r_{FM} = \Delta r_{p}$. The largest pair of values are those for which Δf is the maximum obtainable from available transducers. On the basis of detection alone there is no choice, each pair giving identically the same Δr_{FM} and R. (If one considers search rate, including systems employing simulatneous or mixed pulsing at different frequencies, there may be a choice between these. These considerations have been specifically omitted from the memorandum which is concerned with detection alone).

Since acceptance of the condition $\Delta F \cdot T_{FM} = 1$ is a basic condition for simplifying the comparison of the detection capabilities of the pulse FM and "single frequency" sonars, it might be well to contrast FM sonars with $\Delta F' \cdot T' > 1$ with those for which $\Delta F \cdot T = 1$.

To have the same N for the same source level:

$$N = N_1 \Delta F^1 = N_1 \Delta F$$

$$\Delta F^1 = \Delta F$$

and $T^1 \Delta F^1 = a T \Delta F$

$$T^1 = a T$$

To have the same R:

$$R = R_1 \frac{c}{2} \frac{\Delta F'}{\Delta f'} T' = R_1 \frac{c}{2} \frac{\Delta F}{\Delta f} T$$

$$\therefore \quad \Delta f' = a \Delta f$$

And both satisfy the same $\Delta F_{MIN} = \left(\frac{2v}{c} \frac{\Delta f}{T} \right)^{1/2}$. Thus the sonar with $\Delta F^1 \cdot T^1 = a > 1$ employs "a" times the pulse length and "a" times the bandwidth to obtain the same detection capabilities as the sonar with $\Delta F \cdot T = 1$. The former employs a pulse "a" times longer with the same frequency sweep rate df/dt as the latter but averages over only $1/a$ th of its duration. Thus we feel the comparison of the detection capabilities of the FM and "single frequency" sonars on the basis of the same bandwidth is completely justified. This does not necessarily hold for the comparison of sweep rates which has been specifically omitted in this memorandum.

The FM sonars for which $\Delta F \cdot T = 1$ have the very much simplified equations.

$$R = R_1 \frac{c}{2 \Delta f}$$

$$N = N_1 \Delta F$$

and

$$\Delta F_{MIN} = \frac{2v}{c} \Delta f$$

From these equations it is clear that the input bandwidth Δf alone determines the output reverberation level and the output bandwidth ΔF alone determines the output noise level as long as all other parameters are fixed.

It is further interesting to note that there is a constant ratio between the minimum output bandwidth ΔF_{min} one can

employ with a given input bandwidth Δf. This constant ratio $2\nu/c$ is determined by the maximum range of relative velocities 0 to $\pm\nu$ which one wished to detect with a single locally generated sweep rate. It is further interesting to note the similarity of these equations to those of the "single frequency" ping system, if the ΔF is always kept equal to ΔF_{min}, in that increasing Δf will decrease reverberation and simultaneously increase ΔF_{min} and hence increase noise. The advantage of the FM sonar over the ping sonar lies in the maximum gain factor $\Delta f/\Delta F_{min} = \frac{c}{2\nu} = b$. This maximum gain factor is already large (i.e. for a 15 knot target $b \approx c/2\nu \approx 10^2$) and can be made much larger by employing swept local signals to reduce the effective relative velocity error ν to a very small value as is discussed in paragraph 5 below.

This gain of the FM sonar over the "single frequency" sonar can be employed in many ways in comparison with the "single frequency" sonar. Thus given a "single frequency" sonar of bandwidth Δf_p, one can make the input bandwidth of the FM sonar $\Delta f_{FM} = \Delta f_p$ and $\Delta F = b^{-1}\Delta f_p$ which yields $R_{FM} = R_p$ but $N_{FM} = b^{-1} N_p$ which represents a gain of b in E/N. Or one can split the suppression factor between the two bandwidths, $\Delta F = b^{-x}\Delta f_p$, $\Delta f_{FM} = b^{1-x}$ f_p and reduce noise by b^{-x} and reverberation by b^{x-1}. Thus if the gain is 20 db one can apply it 10 db on E-R and 10 db on E-N.

b. Reverberation

Thus for E-R = 10 db, the following FM sonars are possible, all of which have the same $\Delta f = 10$ cps and $\Delta r = 100$ yds.

1) $T_{FM} = 0.1$ sec, $\Delta F = 10$ cps

2) $T_{FM} = 1.0$ sec, $\Delta F = 1$ cps

3) $T_{FM} = 10$ sec, $\Delta F = 0.1$ cps

4) $T_{FM} = 100$ sec, $\Delta F = 0.01$ cps

Since a 15 knot submarine will stay in an 100 yard range interval for 12 seconds, the 100 second system above could not be used for this target. The locally generated comparison pulse may be extended to twice the travel time through the zone plus the pulse length, while preserving the same slope df/dt to insure that a signal from any point in the zone will be compared with the locally generated pulse for 10 seconds.

c. Noise

The noise in an FM sonar is limited by its output bandwidth; thus the long pulse FM sonars with smaller ΔF than for the "single frequency" pulse sonar require proportionately lower source levels; i.e., for the T_{FM} equal to 10 seconds sonar above, the required source levels given below are 20 db below those of the $T_P = 0.1$ sec ping sonar.

I Zone	$S_o = 88$ µby	
II Zone	$S_o = 98$ µby	$E - N = 10$ db
III Zone	$S_o = 106$ µby	$E - R = 10$ db

This is the minimum FM sonar which will satisfy the minimum requirements of $E - N = 10$ db and $E - R = 10$ db. As indicated above other FM sonars can be designed employing higher source level and/or greater input bandwidth to increase $E - N$ or $E - R$. Thus a sonar with the same source levels per zone as the "single frequency" sonar and $\Delta F = 1$ cps, $T = 1$ sec, and

$\Delta f = 100$ cps will have $E - N = 20$ db and $E - R = 20$ db. Or with the same source levels per zone as the "single frequency" sonar and $\Delta F = 5$ cps, $T = 0.2$ sec, and $\Delta f = 500$ cps will have $E - N = 13$ db and $E - R = 27$ db. The faster frequency sweep rate systems employed have to be examined for feasibility in terms of the necessary bandwidth.

e. Doppler

In an extreme case of doppler shift, a 15 knot submarine would have a 10.5 cps shift which will cause a range error of $10.5/0.1 \times 100 = 10500$ yds. This shift has the advantage that the reverberation might be lower on this filter. This large range error due to dopple ambiguity can be removed by determining the arrival time of the echo within accuracy dependent on the echo to noise ratio.

4. Noise Pulse

a. System

The system is assumed to be an active correlation sonar employing pseudorandom noise generators. In this system the broadband signal from one generator is transmitted and the returning echo is crosscorrelated with the output of a second generator which is identical with the first but started at a later time. Only when the delay time between the two generators matches the water travel time to the target and back are the two signals correlated. By employing the shift register of the function generator as a delay line to cover short range intervals and other function generators with different delays for longer range intervals one can observe all zones simultaneously.

To make the system completely comparable with the pulsed "single frequency" and FM sonars, a correlator must be employed which is insensitive to the phase of the signal carrier or midfrequency but portrays the envelope of the correlation function. Several such correlators have been proposed, the most promising of which may be the heterodyne correlator. This correlator will show an output at the heterodyne frequency plus any doppler difference between the two channels and thus requires narrow bandpass filters in place of the usual lowpass filters to do the final averaging.

b. Reverberation

The range resolution of an active noise sonar of this type is $\Delta r_N = \frac{c}{2} \tau_{corr} \cong c/2 \Delta f$ and as such is identical with that for the pulsed "single frequency" and FM sonars above which have the same signal bandwidth. All back scattered signals arriving within a correlation time $\tau_{corr} \cong 1/\Delta f$ of the echo will also correlate with the delayed signal which matches the echo. This will yield a systematic return from reverberation in the output of the correlator which is essentially the same as the reverberation observed in the FM and ping sonars. Reverberation signals from ranges such that the delay is not within the correlation time of the echo will be uncorrelated and will yield a random or noise signal in the output of the correlator. For a pulsed system such as we are considering the ratio of the random output to the systematic output is demonstrated below to be equal to the ratio of $\overline{R}_1$, the reverberation averaged over the pulse duration, to R_1, the reverberation per unit range

interval return from the range of the target. Thus

$$\frac{\text{Random return}}{\text{Systematic return}} = \frac{\left(\int_{r-L/2}^{r+L/2} R_1\,dr\right)\frac{\Delta F}{\Delta f}}{\left(\int_{r-\frac{\Delta r}{2}}^{r+\frac{\Delta r}{2}} R_1\,dr\right)} = \frac{\left(\int_{r-L/2}^{r+L/2} R_1\,dr\right)\frac{\Delta r}{L}}{R_1\,\Delta r} = \frac{\bar{R}_1}{R_1}$$

where $L = cT_N/2$. Here it is assumed that the output filter ΔF is set equal to the reciprocal of the T_N pulse duration and the reverberation is constant over the range interval Δr. When the target is located at a maximum in the reverberation versus range curve the average reverberation will be lower then the reverberation at the target range and the random component will be small compared to the systematic component of the reverberation in the output of the correlator. When the target is located at a minimum in the reverberation versus range curve the reverse is true. In the former case which is probably the LORAD situation the noise sonar is comparable with the pulsed FM and "single frequency" sonars above. In the later case the noise sonar is inferior to the other two sonars in reverberation suppression.

c. Noise

The output noise of the correlation sonar due to input noise is limited by its output bandwidth just as in the FM sonar. It therefore has the same advantage of FM sonar over ping sonar.

d. Doppler

Since doppler which is time compression or expansion of the signal does not produce the same result as time delay of the signal for noise signals, this system does not have the doppler-range ambiguity of the FM system. It therefore has all of the advantages of the

long pulse "single frequency" sonars for the detection of moving targets.

5. Swept FM or Noise Pulse-Processing for Moving Targets

This technique which has been developed for the noise correlation and FM sonars sweeps the delayed signal to exactly match the range rate of the target. Thus it can keep contact with the target over a much longer averaging time. This increased relative "stability" of the target can be employed either to reduce reverberation or to reduce noise. For example if by compensating for its range rate the 15 knot target can be kept within the 100 yd range interval for 120 seconds in place of 12 seconds one can employ longer pulses and longer averaging times and reduce noise. However averaging times longer than 60 seconds are only possible if one can tolerate crosstalk from the transmitter and adjacent reverberation while receiving from the first zone which will greatly increase the frequency rejection requirements on the filters. Alternatively one can say that the target would now be kept in a 10 yd range interval for 15 seconds so one can increase the bandwidth by ten times keeping the output filter at 0.1 cycles and obtain ten times the range resolution and reduced reverberation. Of course a ping sonar with this new bandwidth would do the same, but would require 30 db more source level.

6. Time Compression Analysis

Techniques exist for the time compression of these signals by a factor of 1000 and thus conduct the multiple processing suggested above at 1000 times the input rate and reduce by a factor of 1000 the number of units required for simultaneous processing.

7. Assumptions: It is well to emphasize the most hazardous assumptions.

a. It is assumed that the 1 kc RL in sea state 2 will decrease with ping length below 1 second. No observations have been made below 1 second. If the converse holds it would indicate that the scatters do not occupy the whole convergence zone. Thus the reverberation level would be higher in some regions and lower in others than that calculated.

b. It is assumed that the reverberation comes equally from all bearings and so may be reduced in the ratio of the beam width to the total horizontal angle. Again there are no observations. If the converse is true the reverberation level would be lower on some bearings and higher on some bearings than calculated.

c. It is assumed that the limiting self noise of the receiving array platform is not much worse than the ambient sea noise, for which there is some evidence. But to assume the linear receiving array will be able to reduce this probably directional noise field as it would an omnidirectional noise field is expecting a lot. If an array were designed to place a null in the direction of the noise field a much larger noise reduction could be realized.

d. Data on the reverberation levels exist only for the first convergence zone. There is no experimental evidence to suggest that the echo-to-reverberation ratio will be the same for all zones.

e. This first order analysis assumes that the variations in the reverberation and noise levels which obscure the target are no larger than their r.m.s. values which are herein calculated.

f. This comparison deals only with detection and does not consider search rate, range and bearing localization, and range rate determination.

8. Summary

a. These sonars all seem to be identical in reverberation suppression if they have the same signal bandwidth Δf.

b. These sonars all seem to be identical in noise suppression if they all have the same total energy in the pulse. The sonar which averages over a long pulse ($T = 1/\Delta F$) can operate at proportionately lower source levels than those which operate with shorter pulses.

c. For all those sonars the minimum output bandwidth ΔF_{min} which determines the output noise level is proportional to the input bandwidth Δf, the reciprocal of which determines the output reverberation level. Thus a decrease in the noise level will cause an increase in reverberation level and vice versa.

d. The advantage of the time averaging sonars is in the constant of proportionately between the ΔF_{min} and Δf. For a "single frequency" sonar this is unity, and for a time averaging sonar this gain factor $b = \Delta f/\Delta F$ is greater than unity. This gain permits larger Δf with smaller ΔF than in the ping sonar with the resultant greater noise suppression for the same reverberation suppression or greater reverberation suppression for the same noise suppression.

e. The maximum gain factor b is $c/2v$ where c is the velocity of sound and $\pm v$ is the range of relative velocities which one wishes to detect with a single locally generated

sweep rate. This gain factor can be made much larger by employing swept local signal to reduce the effective relative velocity error $\pm v$ to a smaller value.